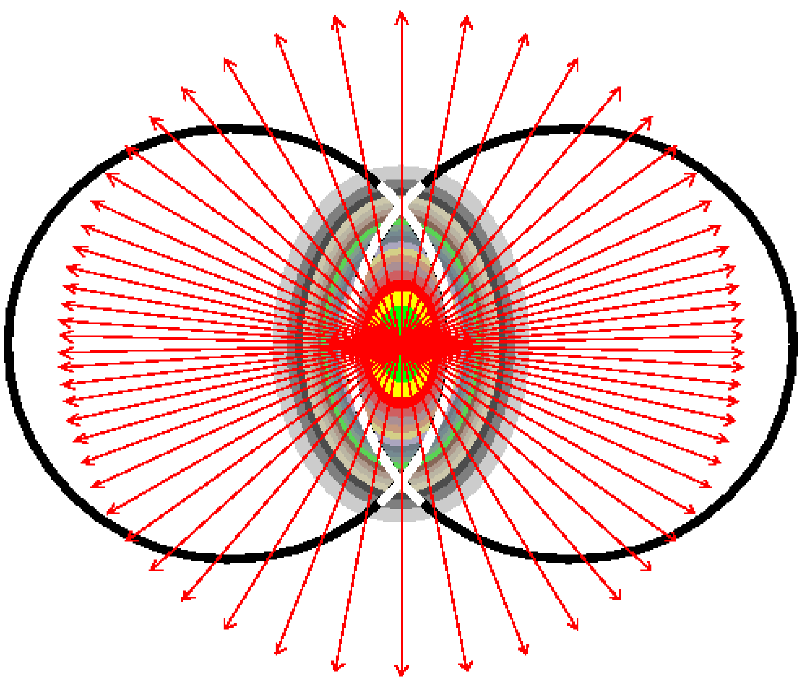
# Relativistic Heavy Ion Collider
# High-pt physics



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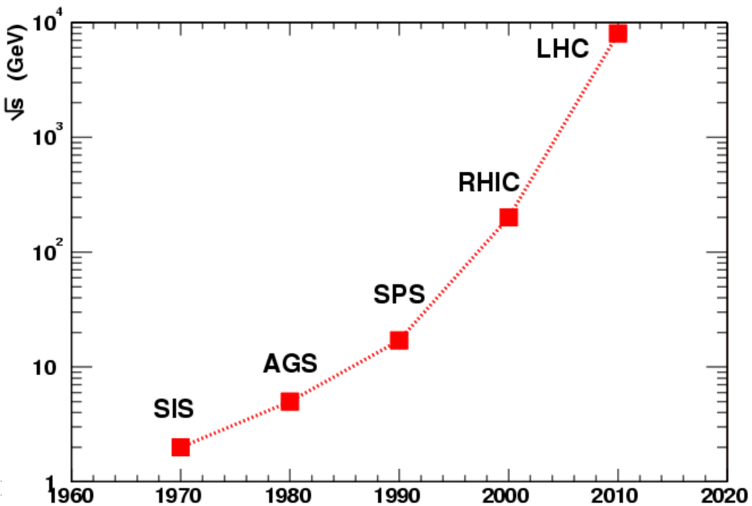
# QCD in Relativistic Heavy Ion Era

low-Q hadronic degree of freedom

| | SIS | AGS | SPS |
|---|---|---|---|
| √s GeV | 2 | 5 | 17 |

high-Q partonic degree of freedom

| | RHIC | LHC |
|---|---|---|
| √s GeV | 200 | 8000 |

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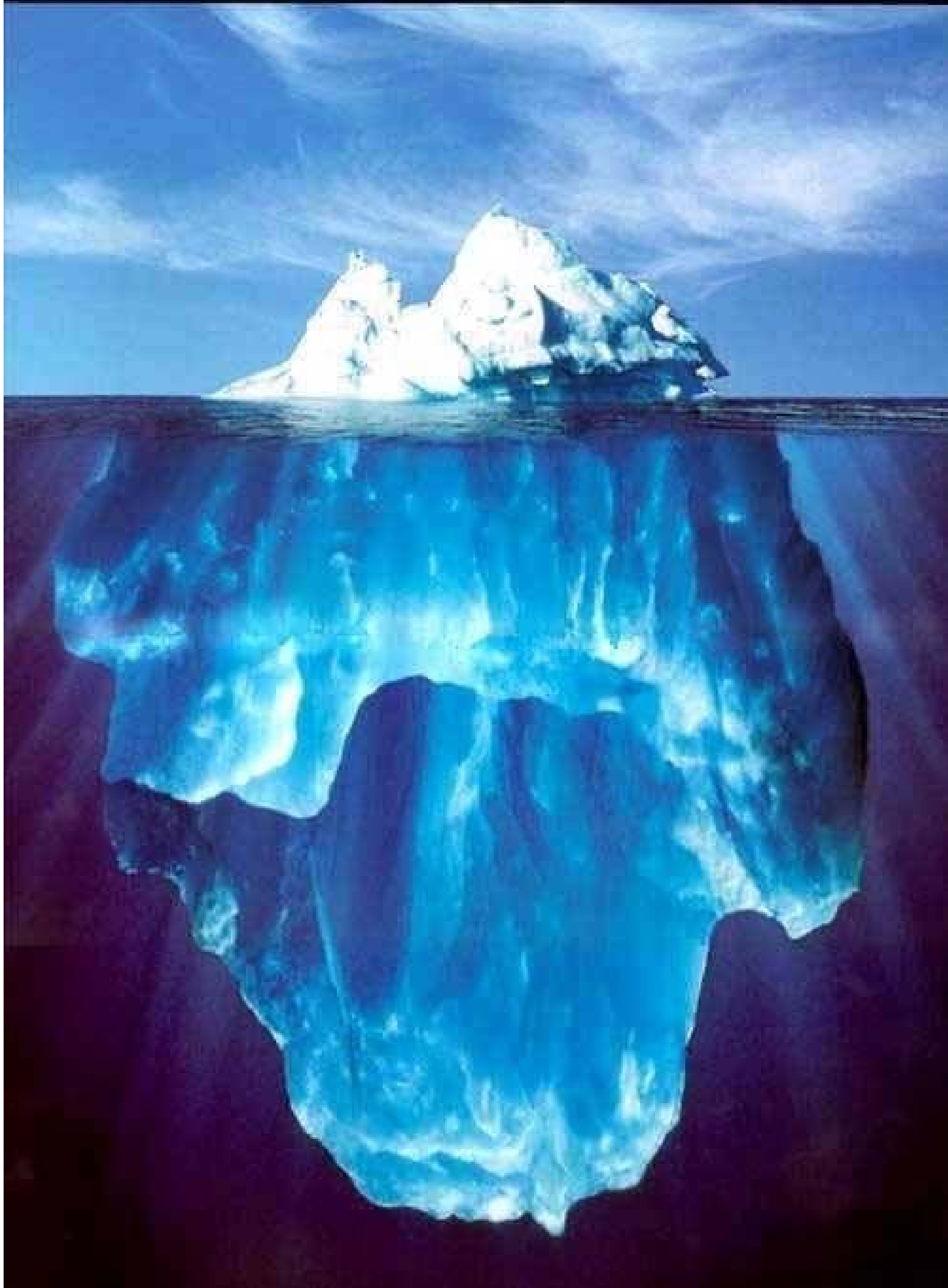
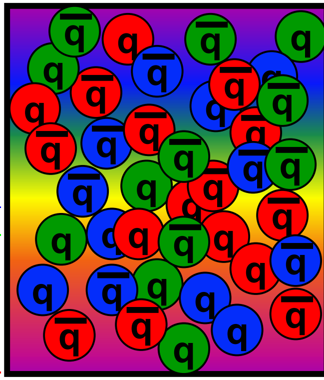
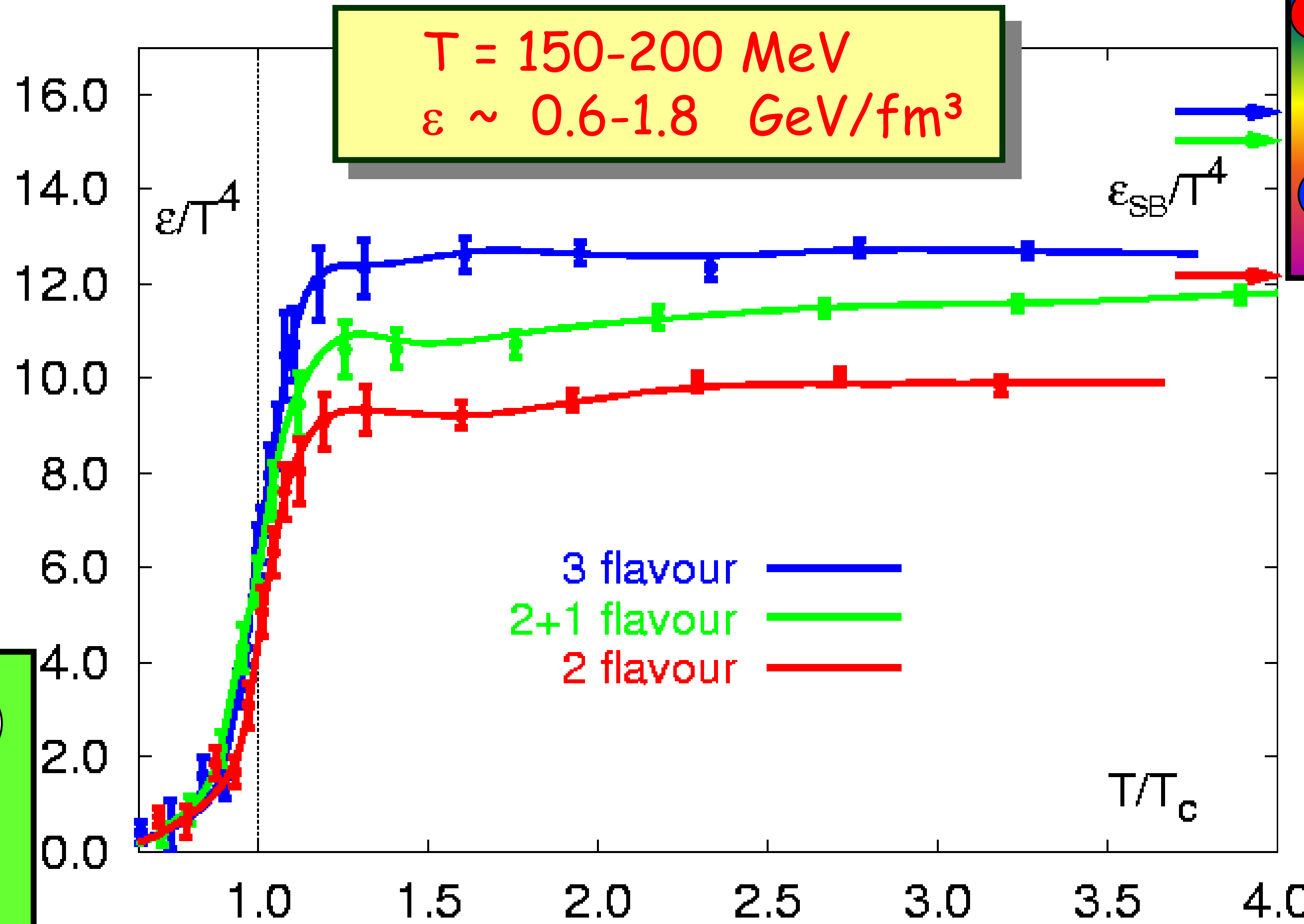
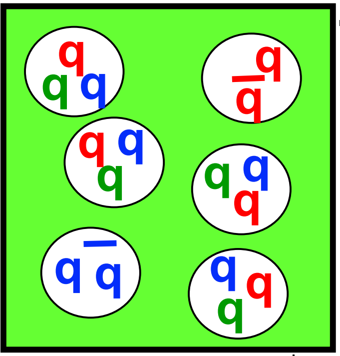


# Deconfinement to Quark-Gluon plasma

Lattice QCD predicts a phase transition to a quark-gluon plasma where the long range confining force is screened.

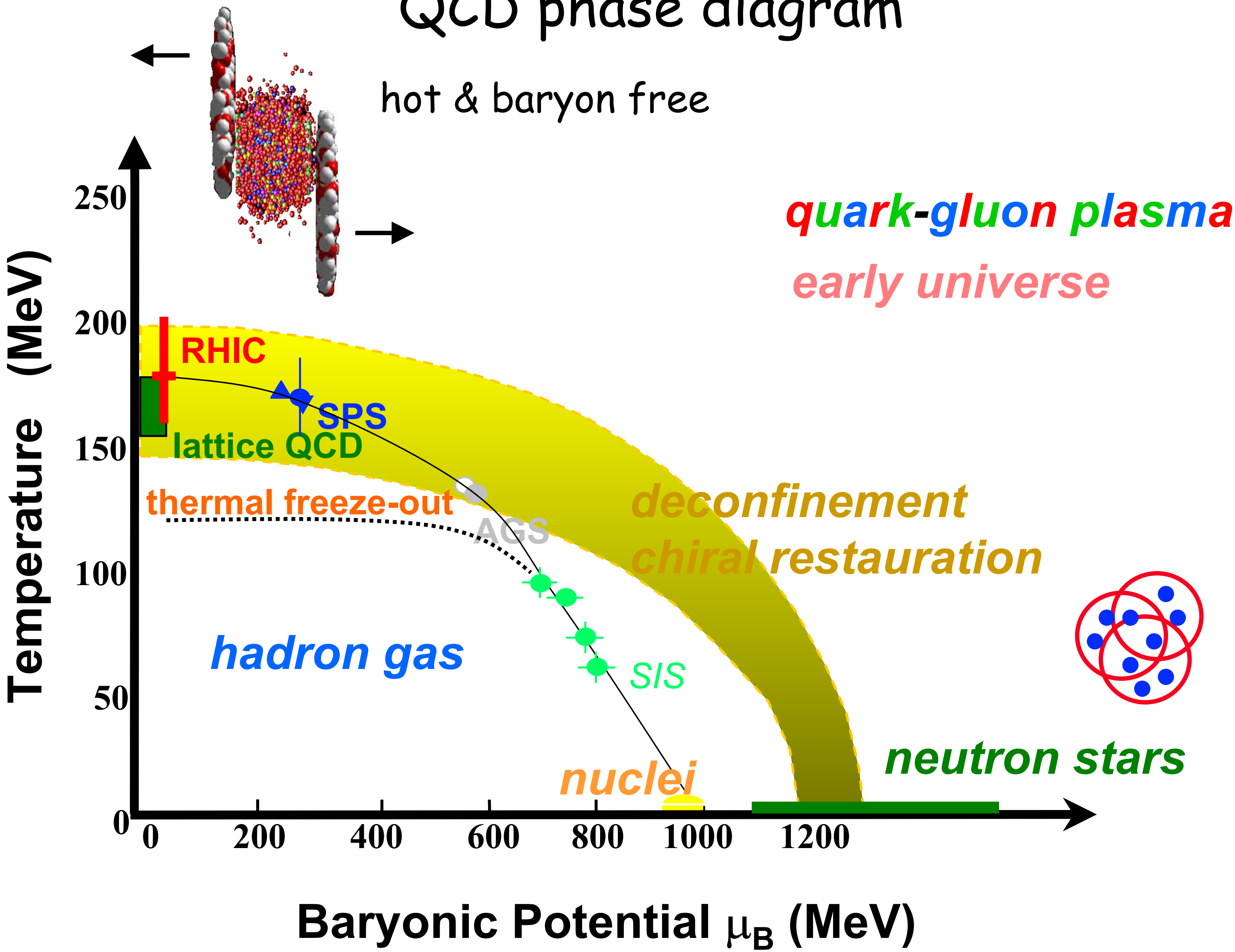



Lect. Notes Phys **583**, 209 (2002)

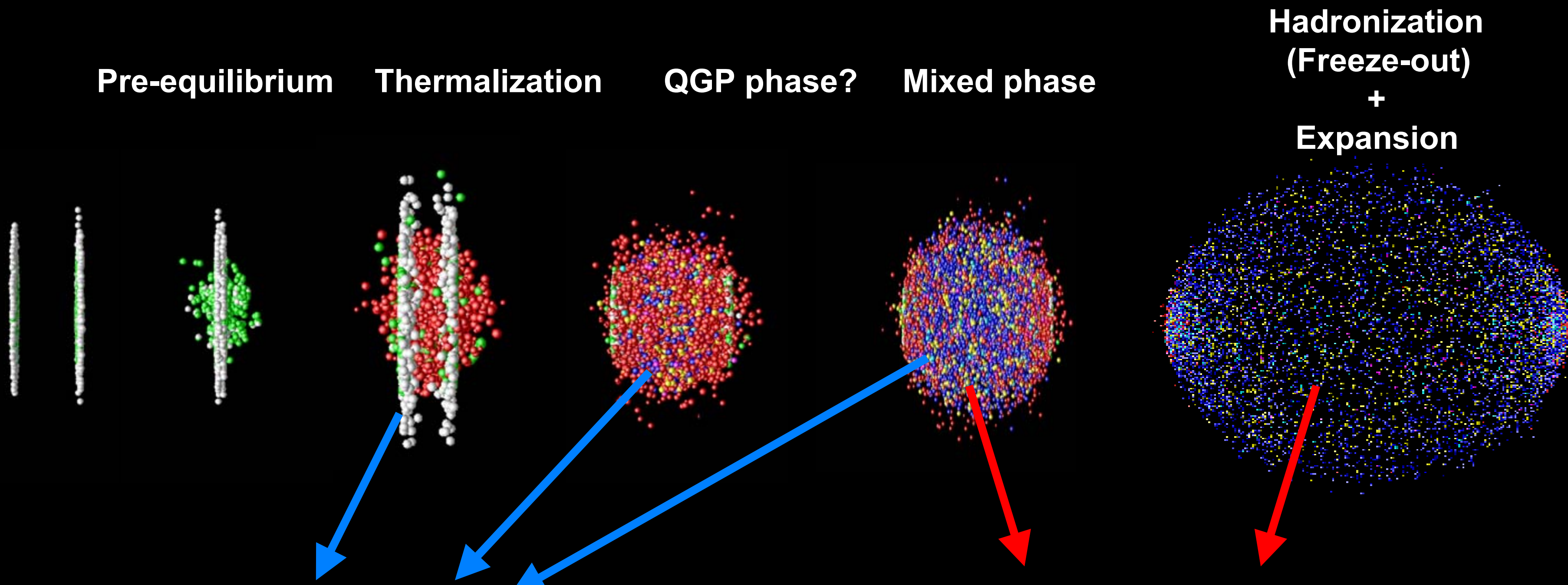
# QCD phase diagram



# Focus of Relativistic Heavy Ion Physics

- Investigate High Density QCD Matter in Laboratory
  - Determine its properties
- Phase Transitions?
  - Deconfinement to Quark-Gluon Plasma
  - Chiral symmetry restoration
- Relevance?
  - Quark-hadron phase transition in early Universe
  - Cores of dense stars
  - High density QCD

# Evolution of Heavy Ion Collisions




$\gamma, \gamma^* \rightarrow e^+e^-, \mu^+\mu^-$

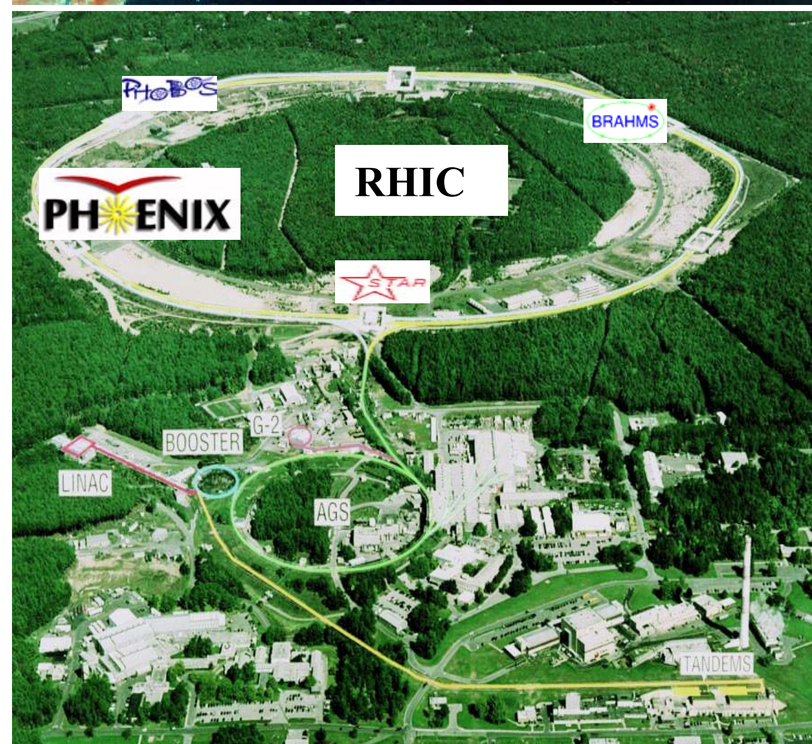
$\pi$, K, p, n, $\phi$, $\Lambda$, $\Delta$, $\Xi$, $\Omega$, d,…

**Hard processes (early stages): Real and virtual photons, high $p_T$ particles.**
**PHENIX emphasis**

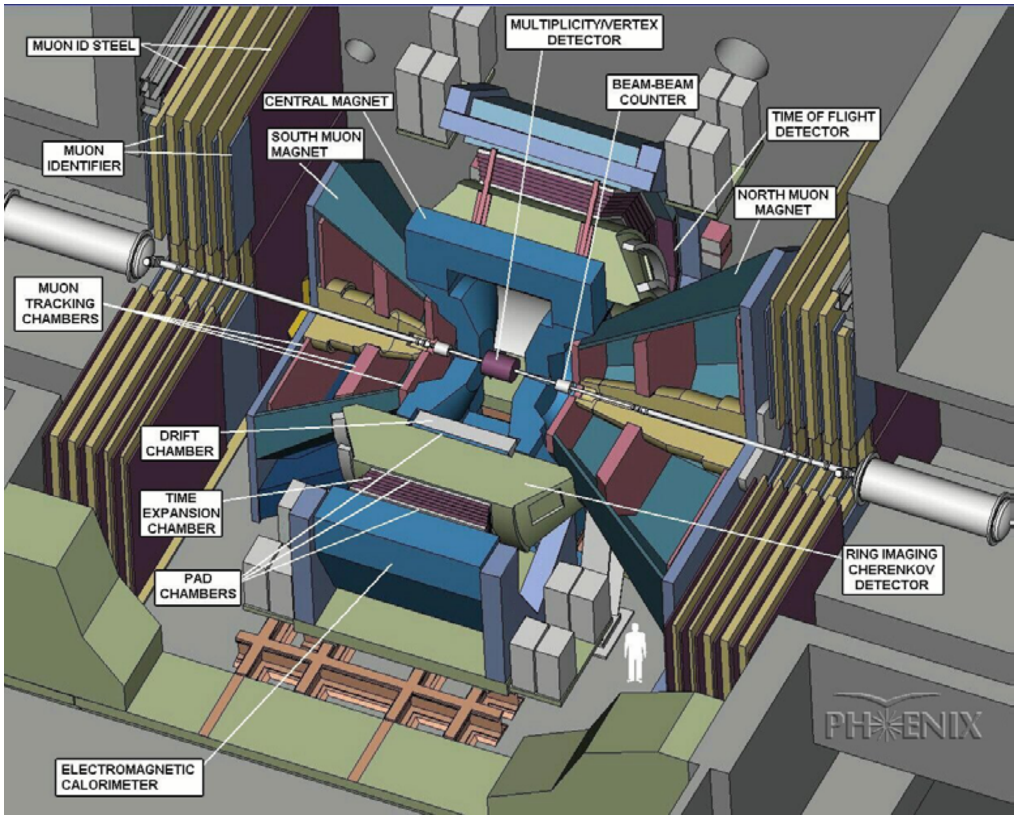
**Soft hadrons reflect medium properties when inelastic collisions stop (chemical freeze-out).**

# The Relativistic Heavy Ion Collider at BNL

- Two independent rings 3.83 km in circumference
  - 120 bunches/ring
  - 106 ns crossing time
- Maximum Energy per N-N collision
  - $\sqrt{s}$ = 500 GeV p-p
  - $\sqrt{s}$ = 200 GeV Au-Au
- Design Luminosity
  - Au-Au $2\times10^{26}$ $cm^{-2}s^{-1}$
  - p - p $2\times10^{32}$ $cm^{-2}s^{-1}$ (polarized)
- Capable of colliding any nuclear species on any other nuclear species



# Pioneering High Energy Nucl. Interaction Exp
# PHENIX



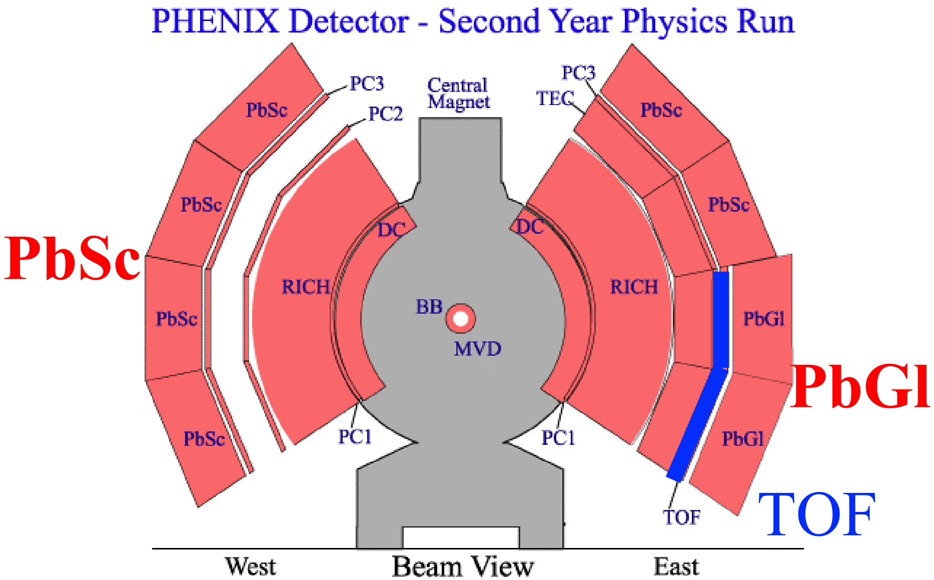

The PHENIX Experiment, main emphasis on electromagnetic probes. Focus:

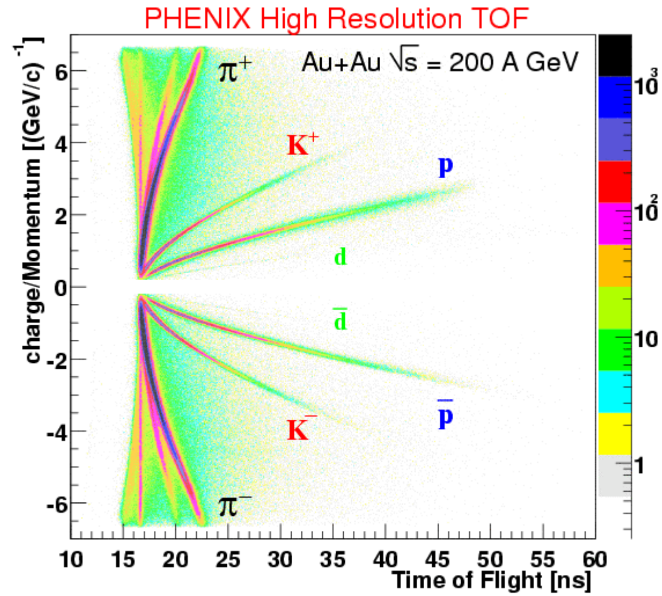
- Rare probes - $J/\Psi$, $\Psi'$, $e^+e^-$, $\mu^+\mu^-$, $\Phi$, direct-$\gamma$ ...
- The spin structure of the nucleons

The Configuration:

- 2 Forward Muon Arms
- 2 Central Spectrometer Arms to measure photons, electrons, and hadrons

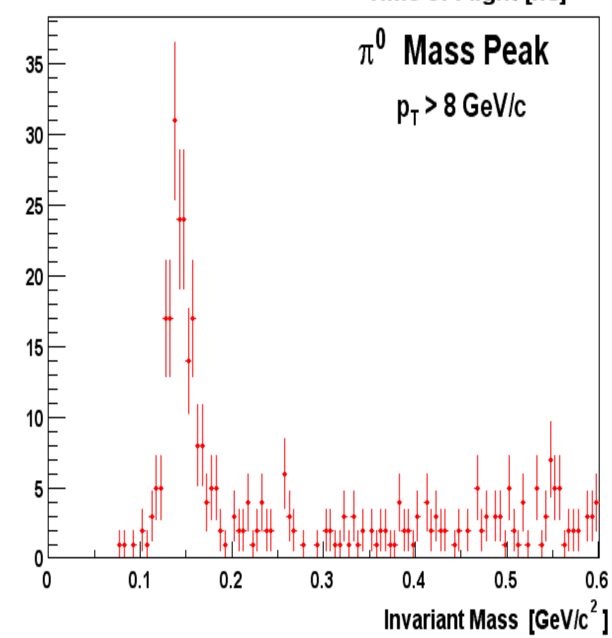
# PHENIX Central Arm




## PID by high resolution TOF

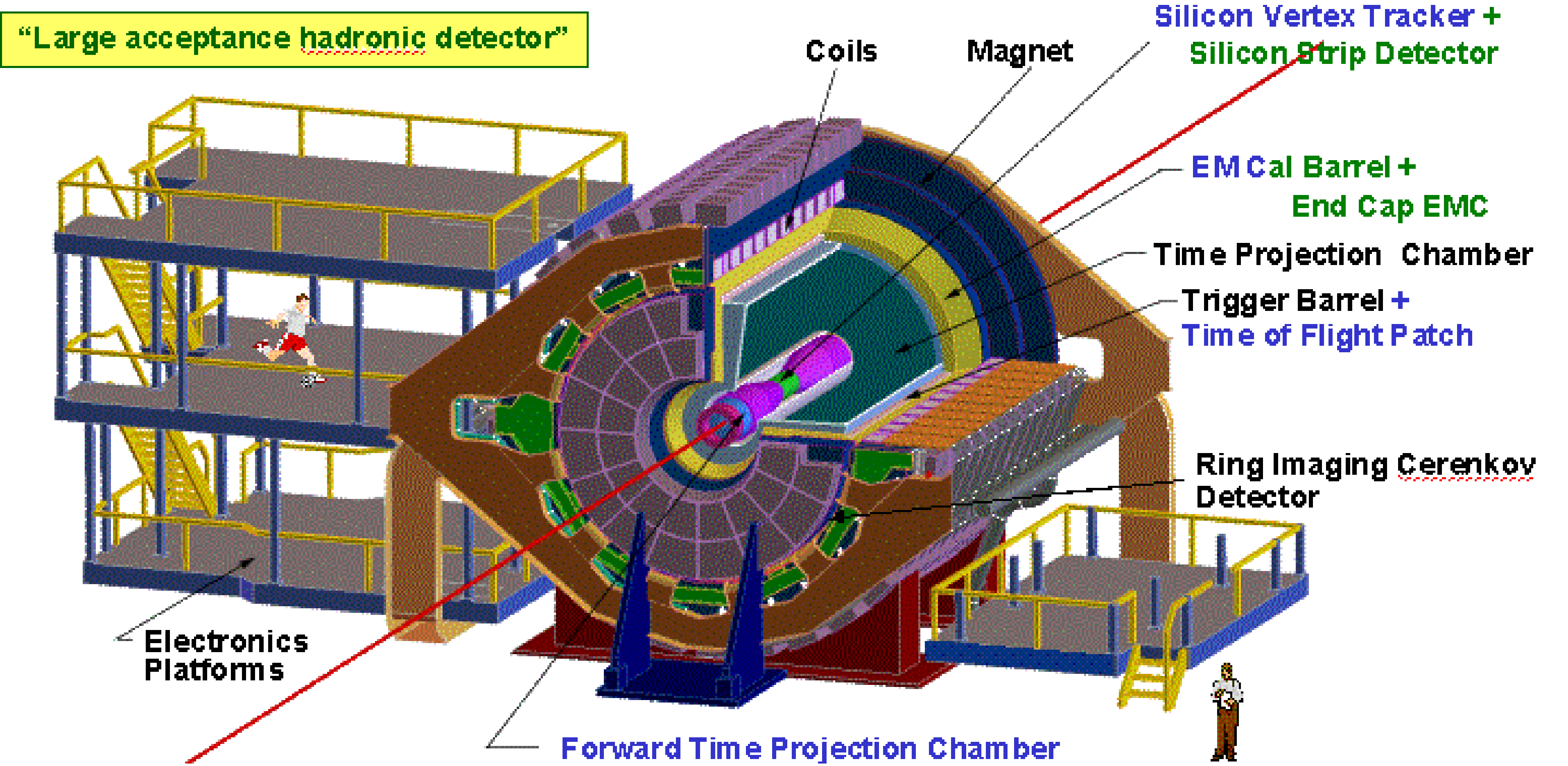
- $\pi$, K < 2 GeV/c
- proton, anti-proton < 4 GeV/c
- $\Delta\phi = \pi/4$




## $\pi^0$ measurement by EMCal

- 1<pt<15 GeV/c
- 6 lead- scintillator (PbSc) sectors
- 2 lead- glass (PbGl) sectors
- $|\eta|$<0.38 at midrapidity, $\Delta\phi = \pi$

# STAR Detector at RHIC




The STAR Experiment, main emphasis on hadronic probes.

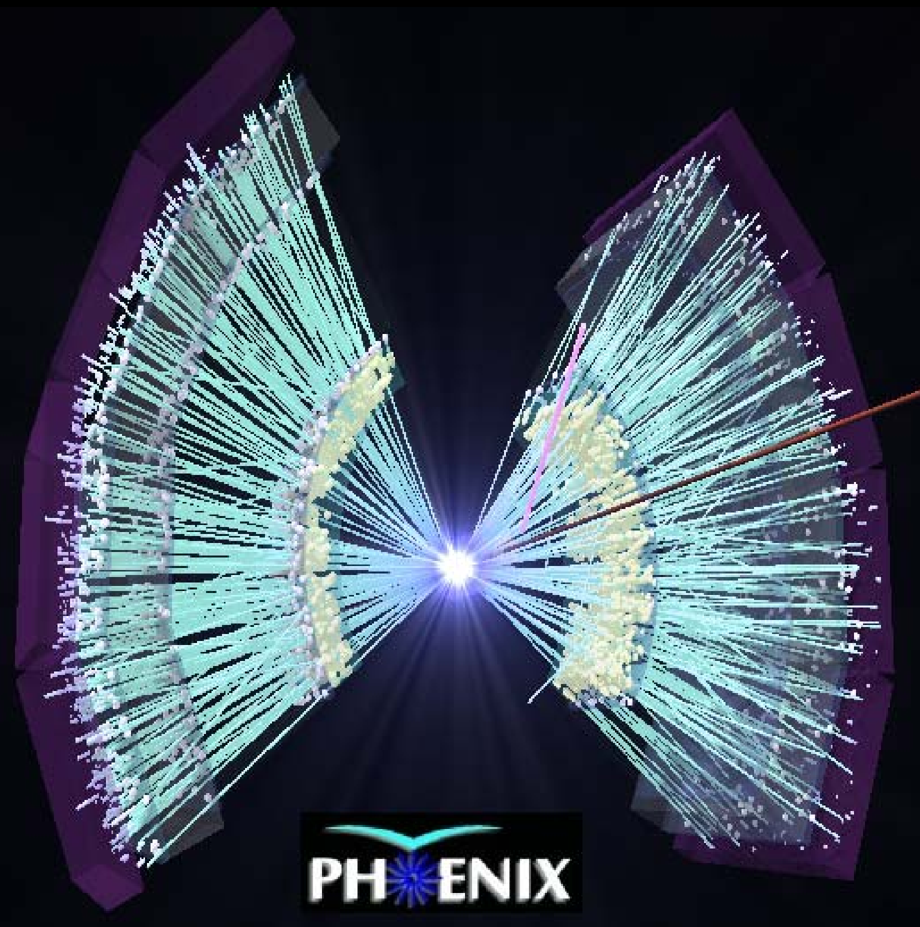
Focus:

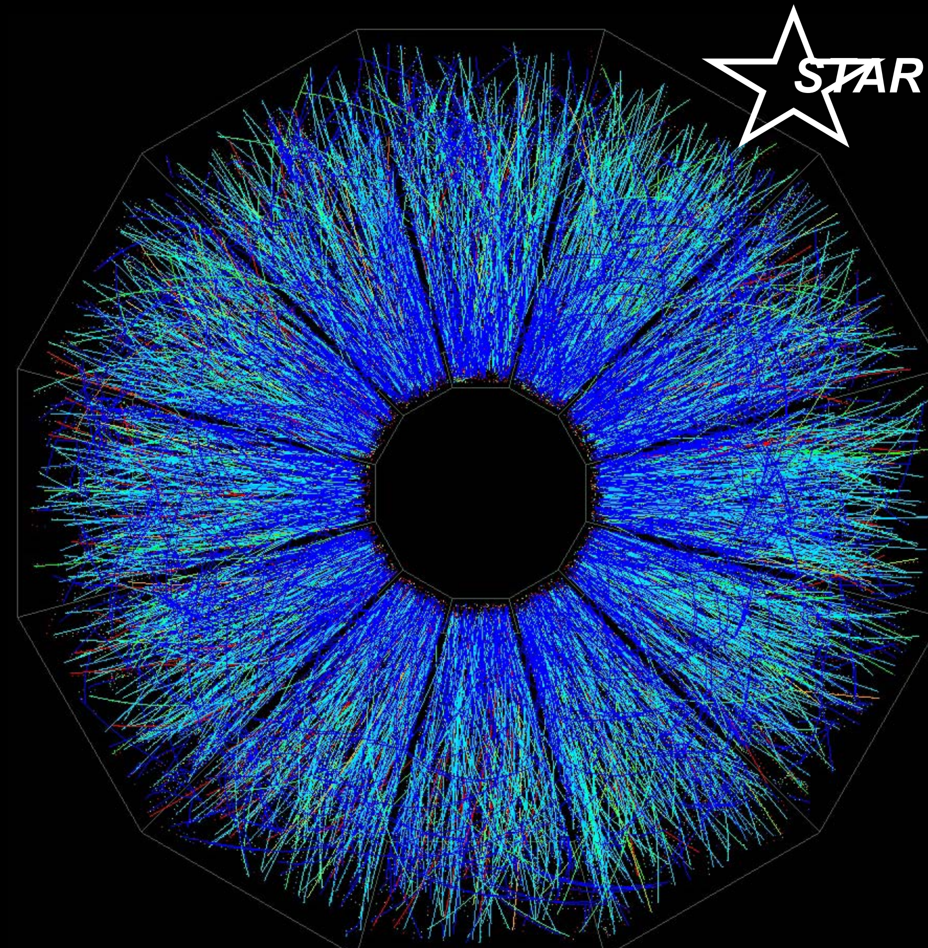
- global observables, event-by-event physics, HBT, strangeness, high-pt jets…

The Configuration:

- large acceptance TPC, Silicon Vertex Tracker, RICH, TOF, EMC…

# Au on Au central event at $\sqrt{s}$=130GeV

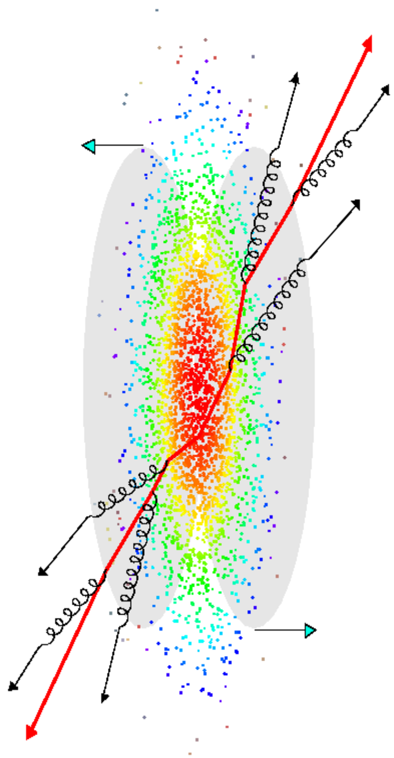



beam view

# Hard scattering in Heavy Ion collisions

schematic view of jet production



Particle production @RHIC

– $dn_{ch}/d\eta\,|_{\eta=0} = 670$, $N_{total} \sim 7500$
  92% of (15,000) all quarks
  from vacuum !

Jets @RHIC:

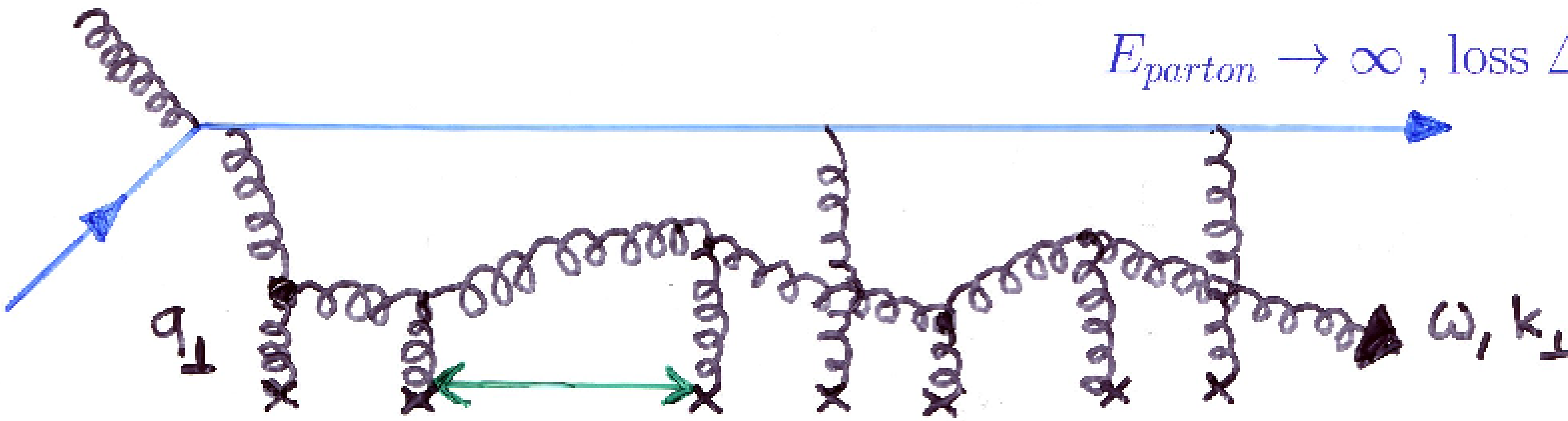
– produced early $\tau<1$fm
– primarily from gluons
– 30-50% of particle production

Observed via:

– fast leading particles
– azimuthal correlations

Scattered partons radiate energy in colored medium →
suppression of high $p_t$ particles

# Paronic energy loss - probe of QGP




mean free path $\lambda > 1/\mu$ .. range of screened gluon interaction

- average energy loss :

$$\Delta E = L \int^{\omega_c} \frac{\omega dI}{d\omega} d\omega \simeq \alpha_s \, \omega_c \; , \; \omega_c = \frac{1}{2}\hat{q} L^2$$

nonlinear interaction of gluons

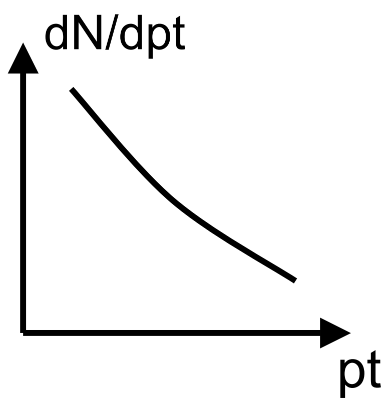
dE/dx ~ few GeV/fm

nontrivial consequence of non-abelian nature of QCD

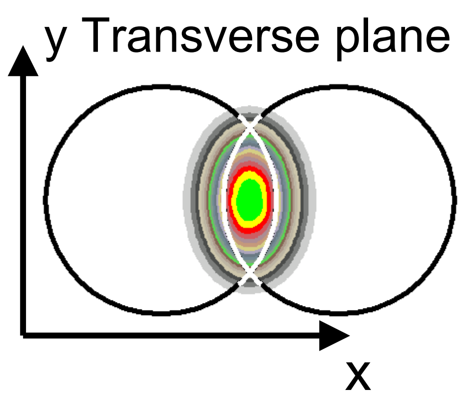
Baier, Gyulassy, Wang, Levin, Vitev et al

# Observables

- Inclusive pt-distribution
  - number of particles per pt-bin.
  - sensitive to partonic energy loss - high-pt suppression.



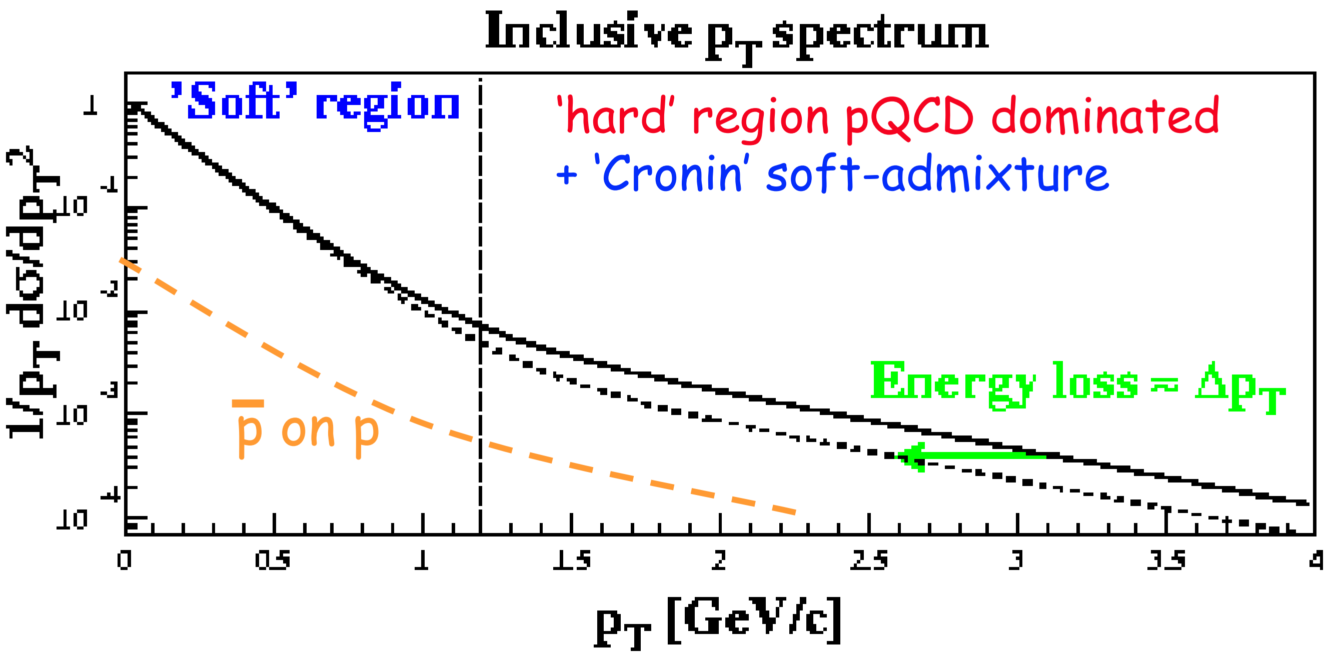

- Azimuthal anisotropy
  - nuclear geometry breaks the azimuthal symmetry
  - sensitive to early dynamics of initial system

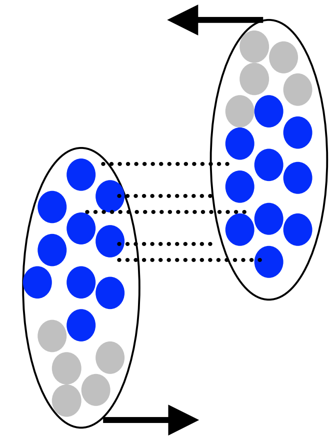



- Flavor composition - particle ratios

- HBT correlations, rapidity distributions, heavy flavors ....

# Inclusive pt-distribution



Nuclear modification factor

$$R_{AA}(p_T) = \frac{1/N_{events}\, d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma_{pp}/dp_T d\eta / \sigma^{pp}_{inelastic})}$$

$R_{AA}$ is a relative yield with respect multiple nucleon-nucleon collisions. If there is no nuclear effect, AA is just uncoherent superposition of pp than $R_{AA} = 1$

# Nuclear Modification of Hadron Spectra

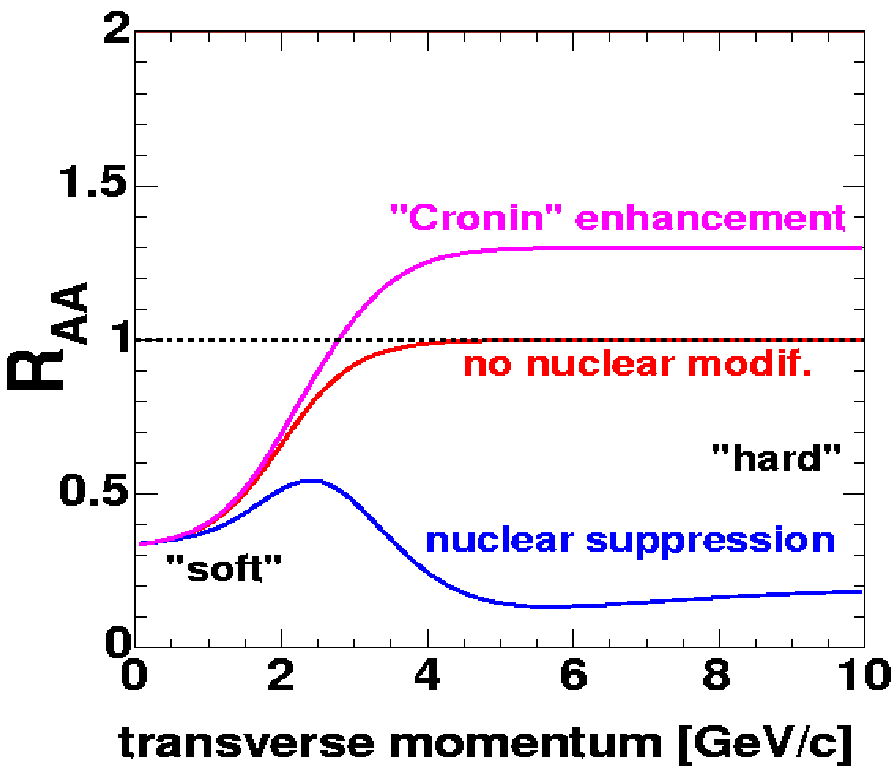
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

**Nuclear Modification Factor:**

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

nucleon-nucleon cross section

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$



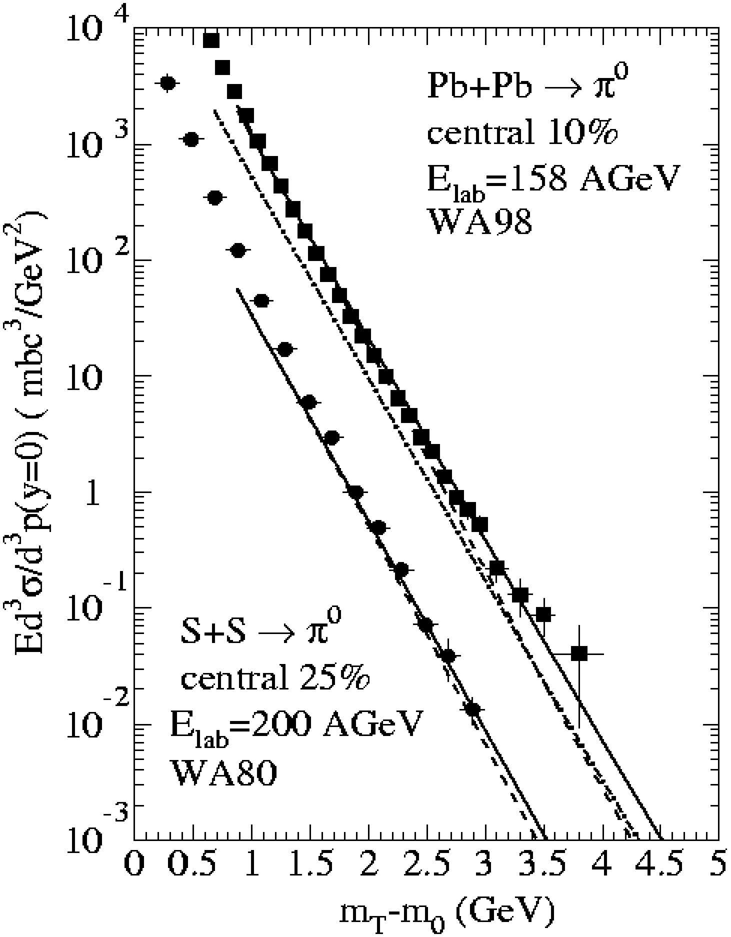

at high-$p_T$:

$R_{AA} > 1$ $k_T$-broadening "Cronin"

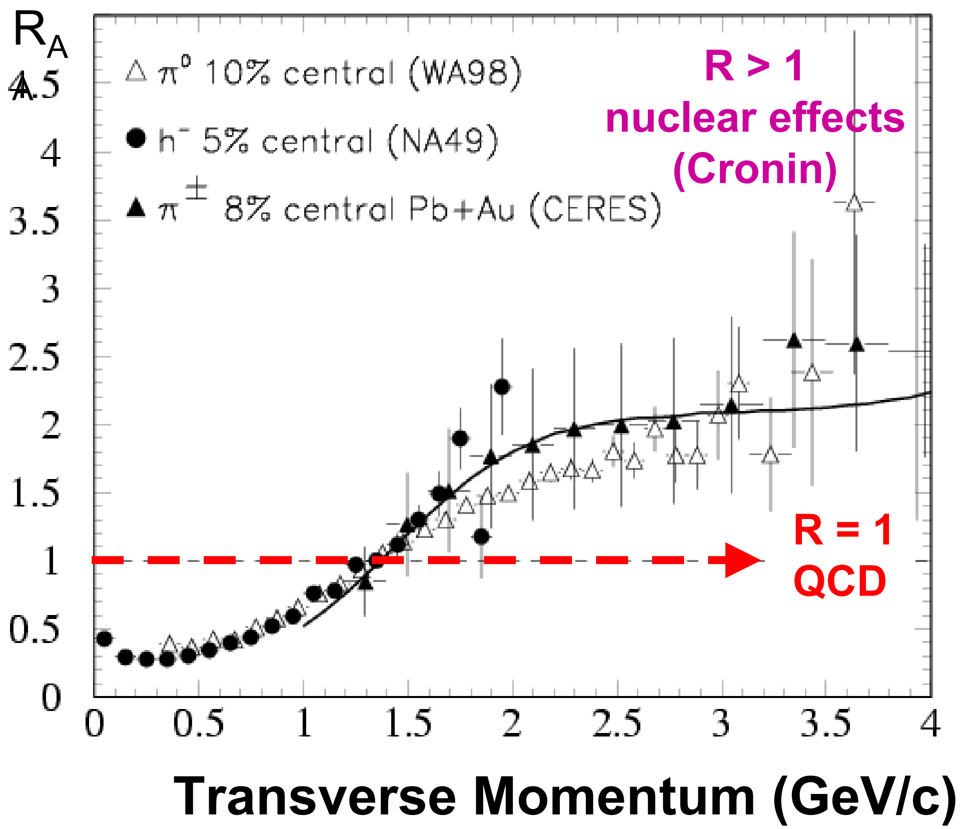
$R_{AA} = 1$ particle prod. $\propto \langle N_{binary}\rangle$

$R_{AA} < 1$ suppression

# pQCD phenomena at SPS



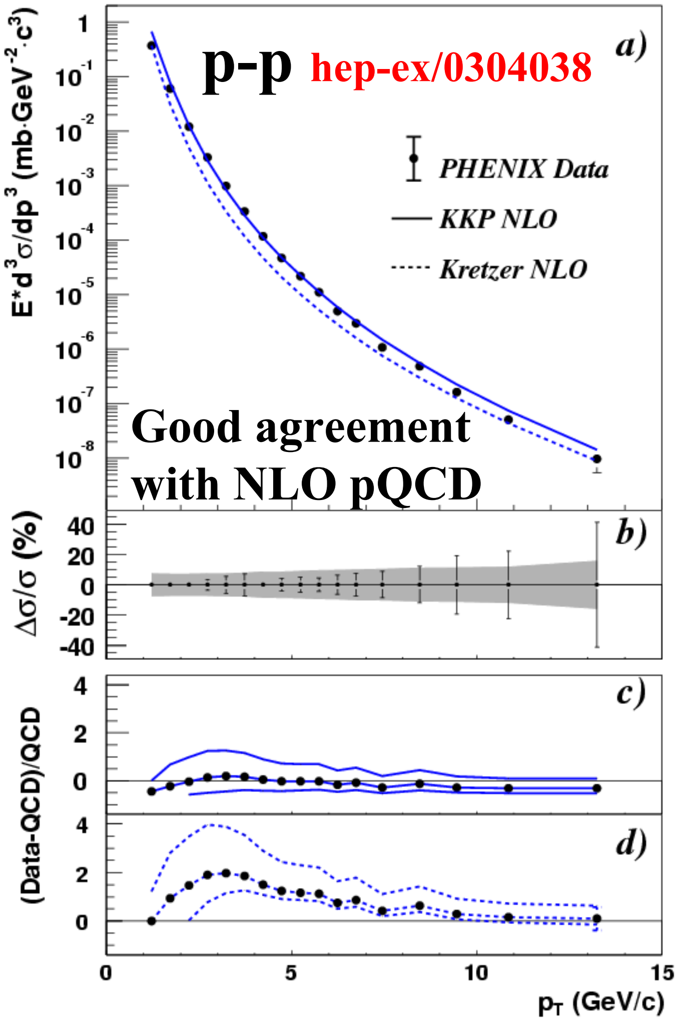

**Where is the jet quenching in Pb+Pb ...**
**X.N. Wang, Phys.Rev.Lett.81:1998**



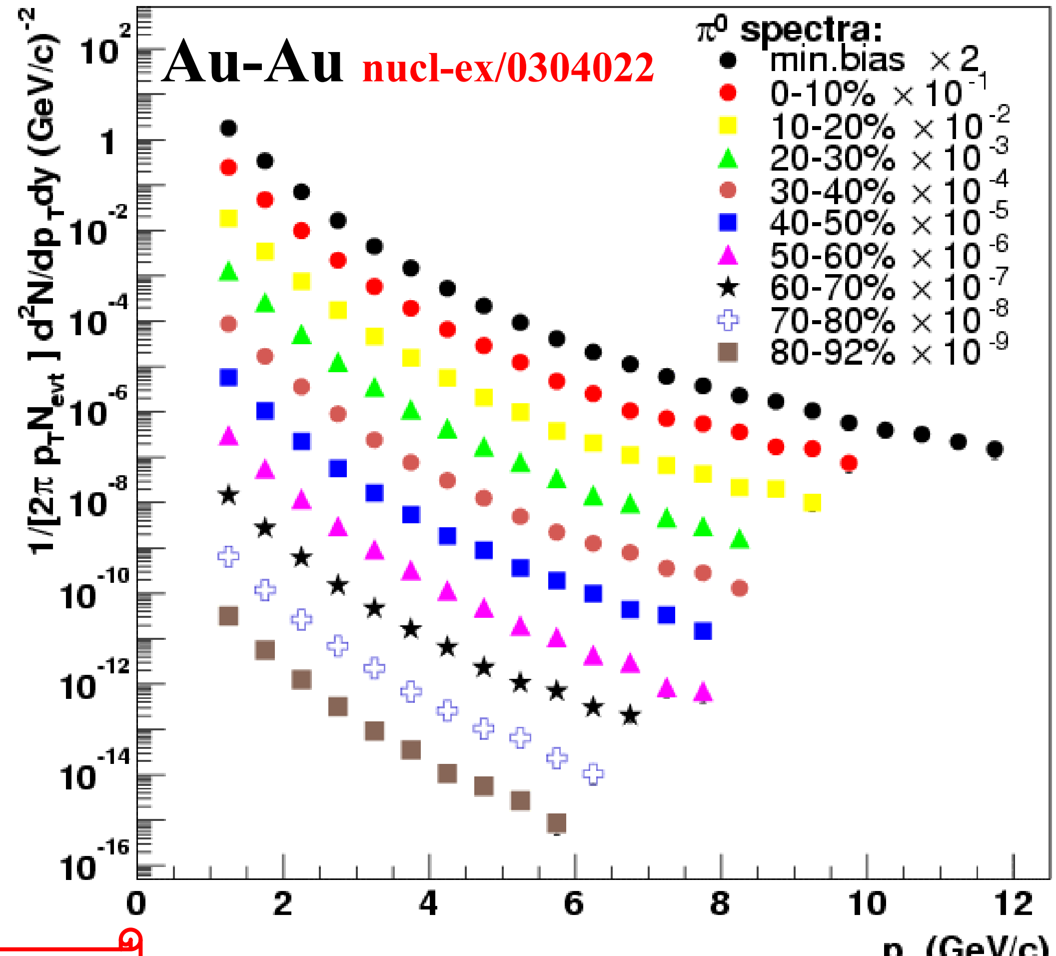

If any suppression , it is overwhelmed by initial state mult. scatt (Cronin effect). Initiated strong interest of RHIC community.

# High $p_T$ p-p and Au-Au $\pi^0$ Results

## Run 2001/2002 p-p + Au-Au $\sqrt{s_{NN}}$= 200 GeV



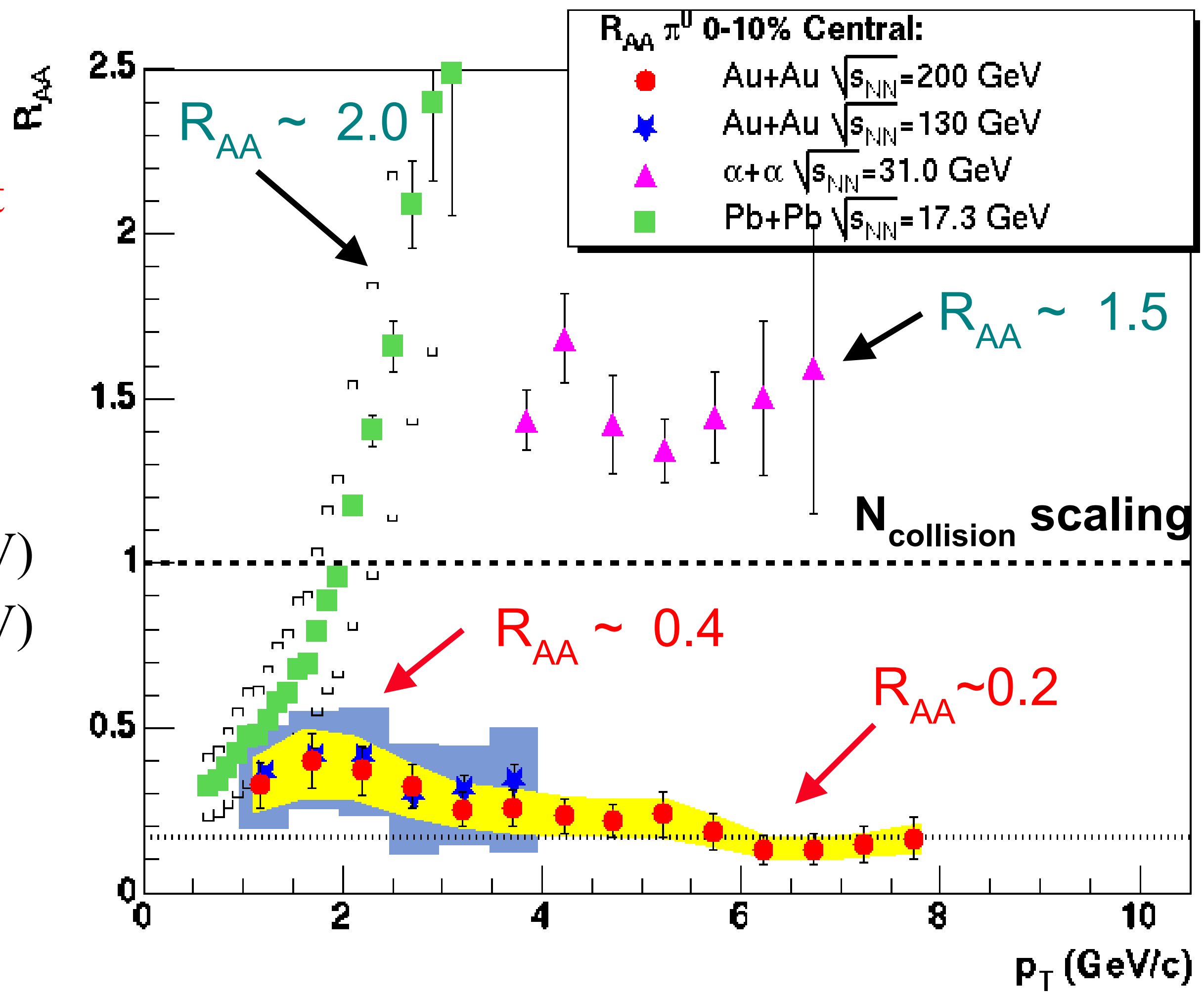

Final
submitted
to PRL




**Data reach pT=12 GeV**

# Nuclear Modification Factor $R_{AA}$

- CERN: Cronin enhancement
  - Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 GeV)
  - α+α ($\sqrt{s_{NN}}$ ~31 GeV)
- RHIC: x4-5 suppression
  - Au+Au ($\sqrt{s_{NN}}$ ~ 130 GeV)
  - Au+Au ($\sqrt{s_{NN}}$ ~ 200 GeV)



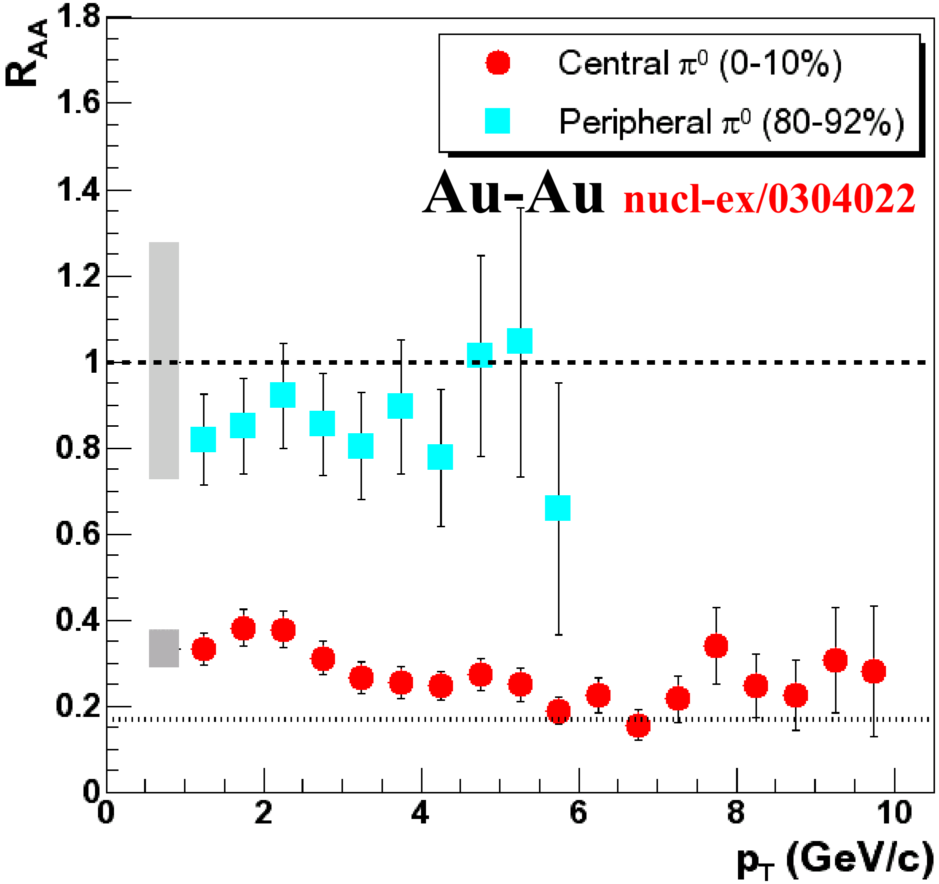
# $R_{AA}$: High $p_T$ Suppression

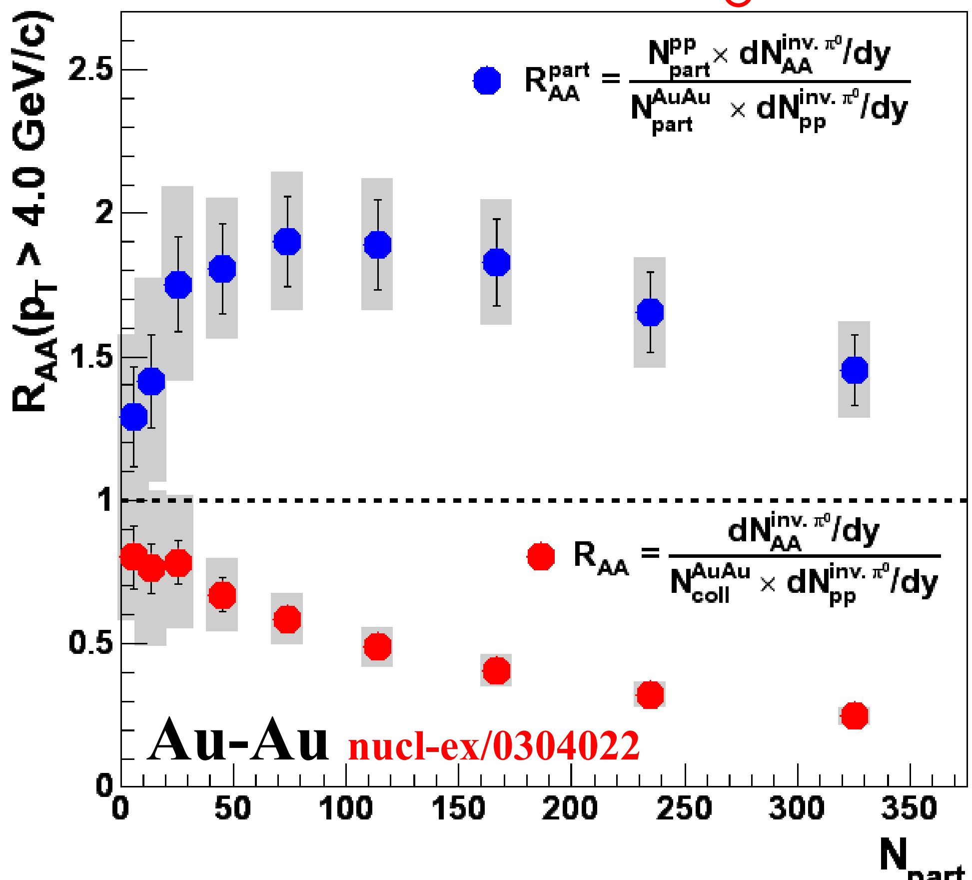
Run 2001/2002 Au-Au $\sqrt{s_{NN}}$ = 200 GeV:

$$R_{AA} = \frac{\mathrm{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\mathrm{Yield}_{pp}}$$

$$R_{AA}^{part} = \frac{\mathrm{Yield}_{AuAu} / \langle N_{part} \rangle_{AuAu}}{\mathrm{Yield}_{pp} / 2}$$

Final submitted to PRL

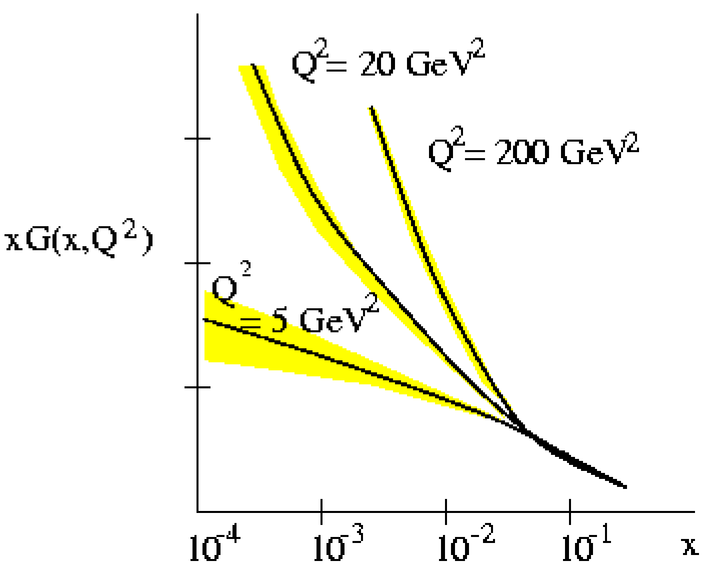


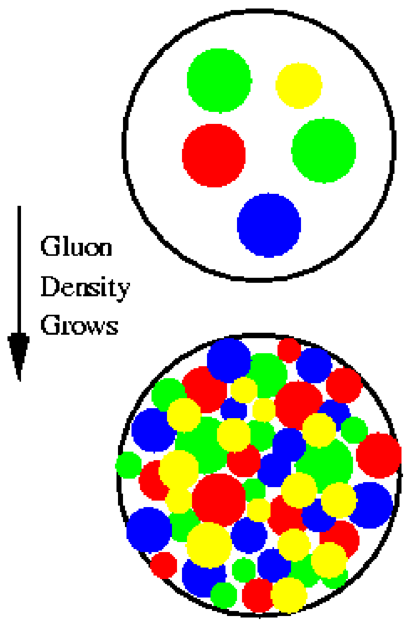



# Suppression: an initial state effect?

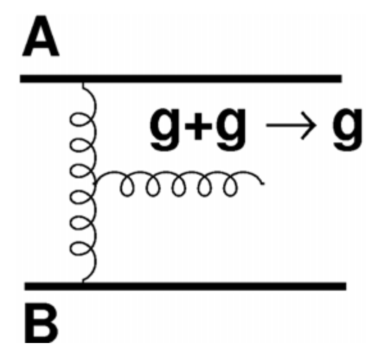
Color Glass Condensate hep-ph/0210033

Gribov, Levin, Ryshkin, Mueller, Qiu, Kharzeev, McLerran, Venugopalan, Balitsky, Kovchegov, Kovner, Iancu




- semi-classical QCD field
- collinear factorization breaks
- "analytic" solution

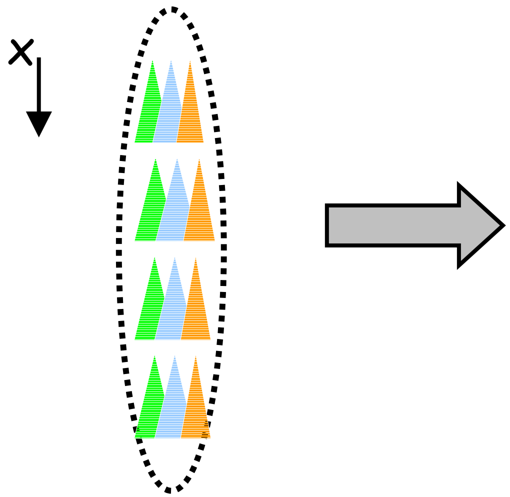



The answer in the dAu data:

- initial state CGC ⟹ $R_{dAu} \leq 1.0$ $\quad R_{dAu} \approx \sqrt{R_{AuAu}}$
- final state Cronin ⟹ $R_{dAu} > 1.0$

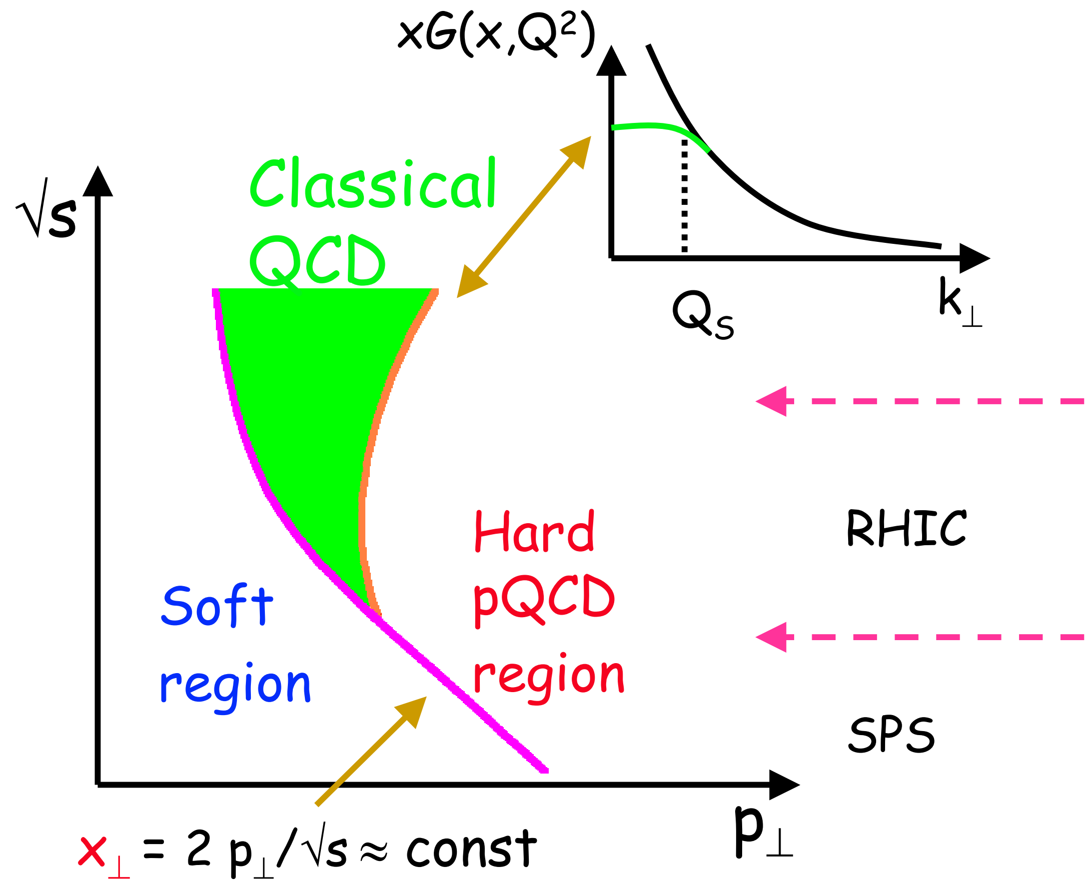
# Model III: gluon condensate at small x

See D. Kharzeev, E. Levin Nucl-th/0108006




At small Bjorken x partonic wave functions starts to overlap

- Saturation
- coherence
- multi-parton correlation breaks down

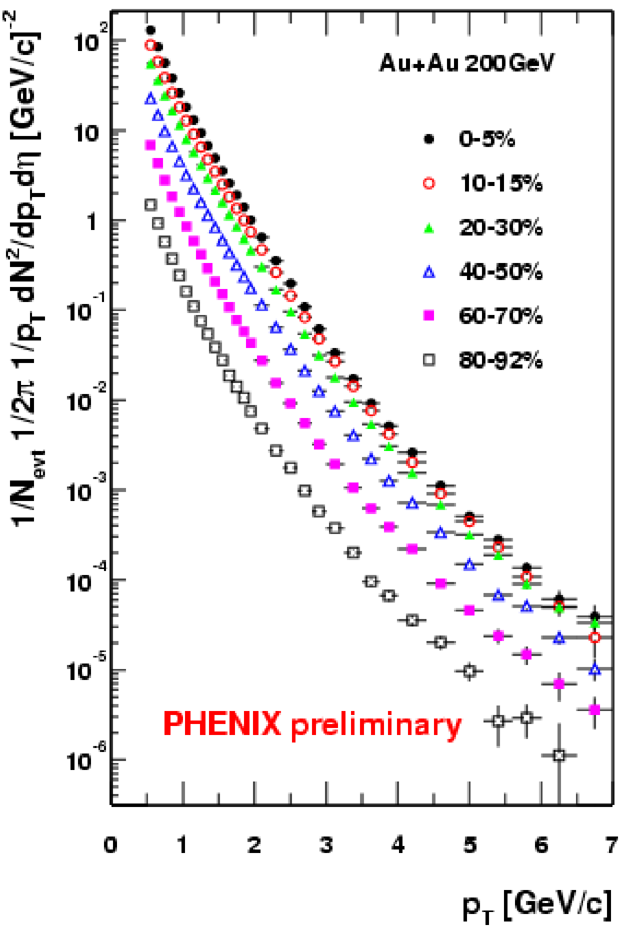


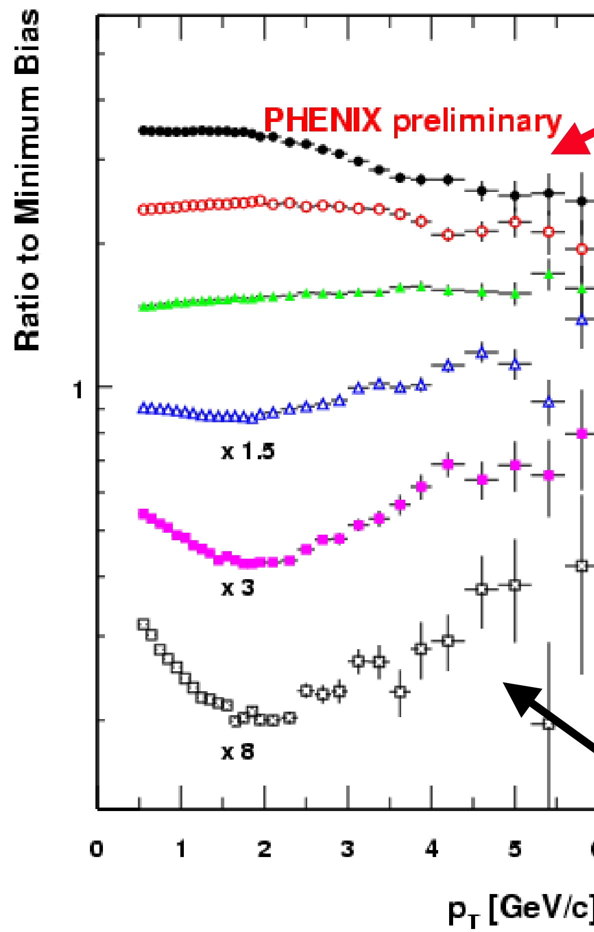

In Classical region the particle production mechanism is 2->1 unlike the pQCD 2->2. This implies:

Below $2^*Q_S \approx 2^*2$ GeV produced particles are not correlated.

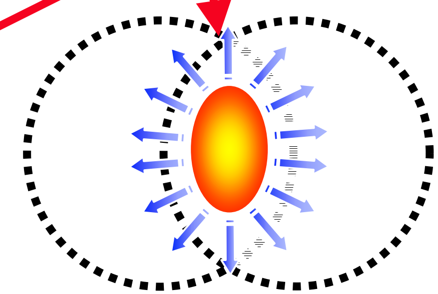
# Initial/final state effects - CGC

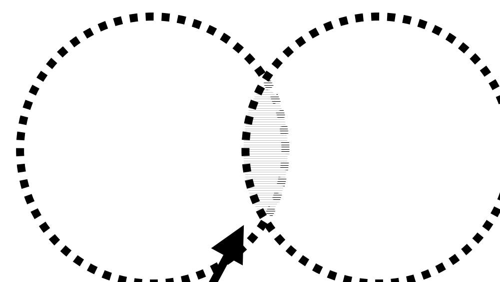
Charged hadrons ratios to minimum bias



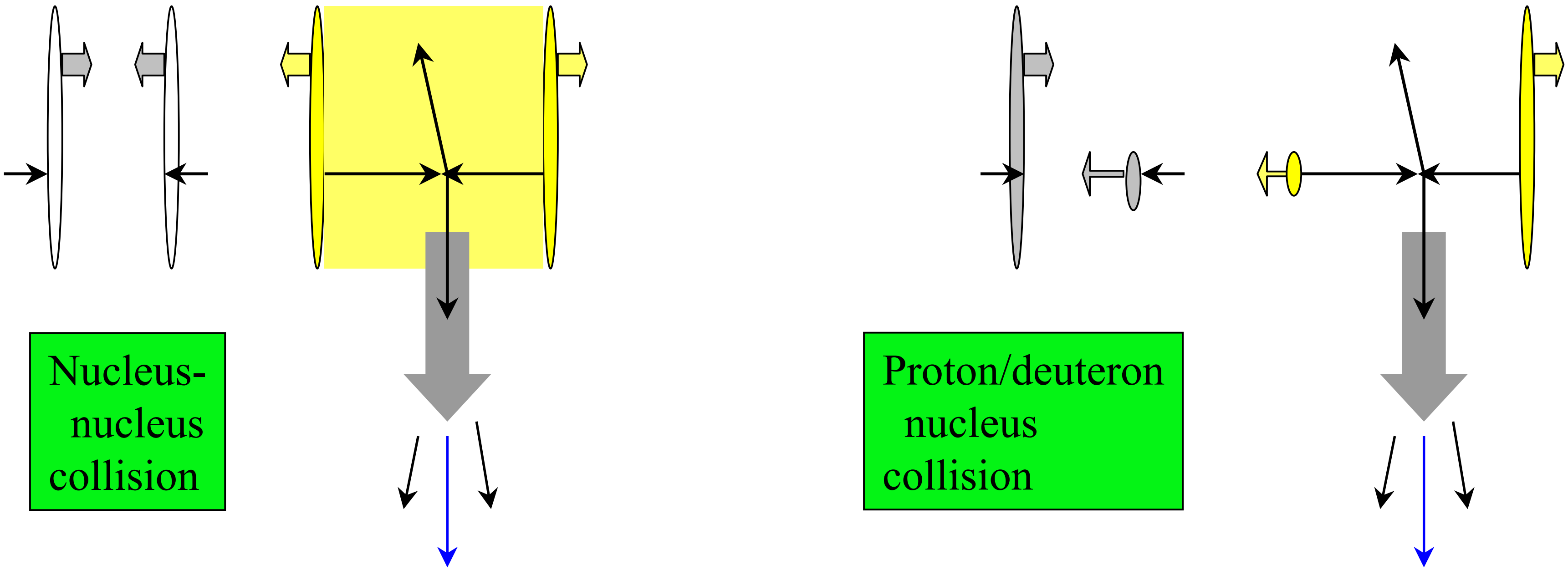

CGC radiation ?





pQCD power law

# p+A (or d+A): The control experiment



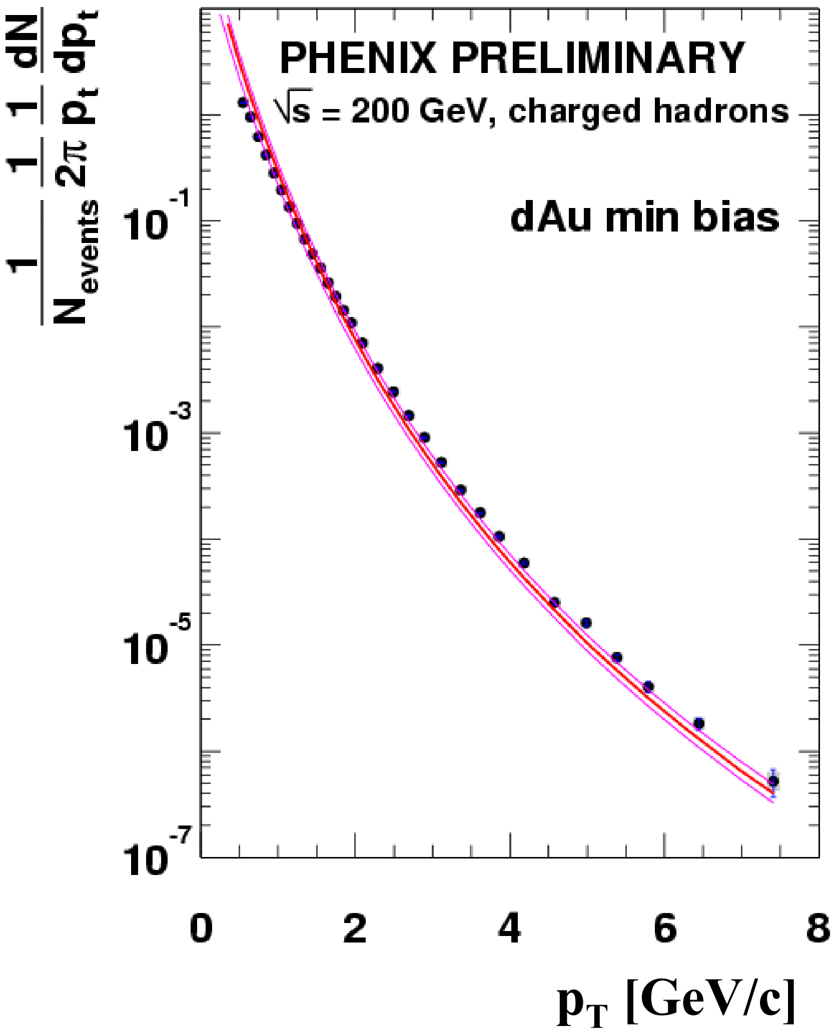

• Nuclear effects other than a dense medium are known to affect hadron spectra (e.g. shadowing, Cronin effect) in p+A and d+A collisions, which do not have a created medium.

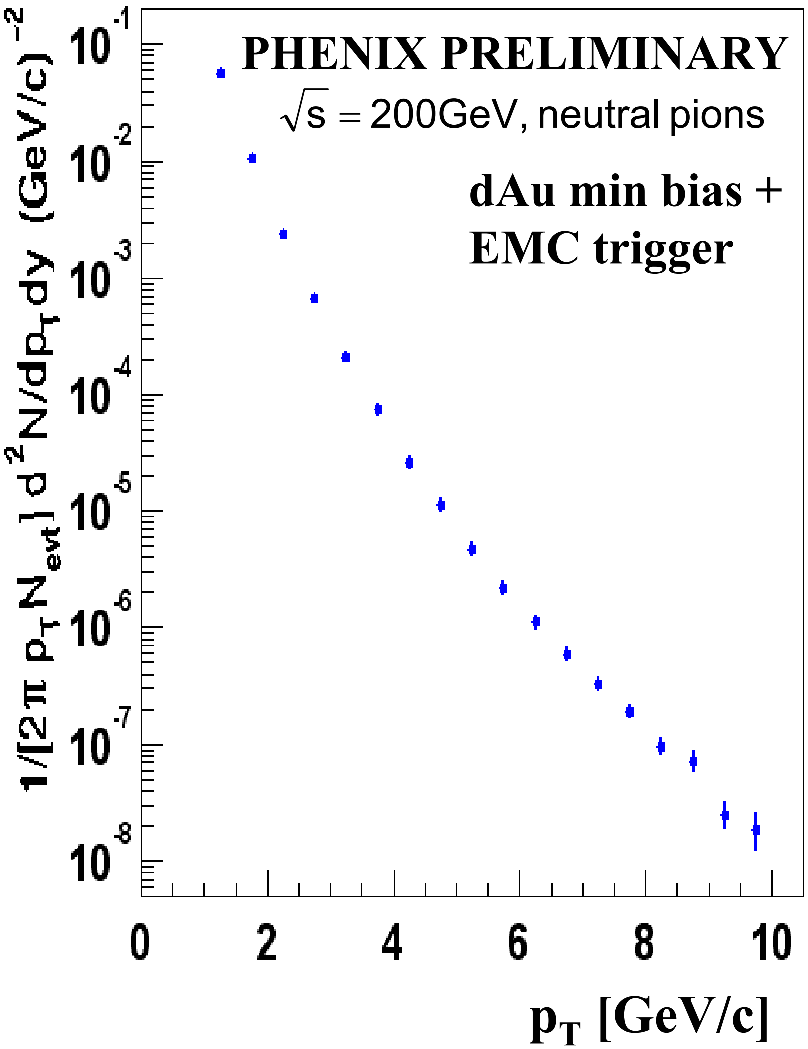
• Could these initial state effects be causing the suppression of high-$P_T$ hadrons in Au+Au collisions?

• If so, then we should see suppression of high-$P_T$ hadrons in d+Au collisions.

# High $p_T$ Spectra in d-Au at $\sqrt{s_{NN}}$ 200 GeV

Run 2002/2003:



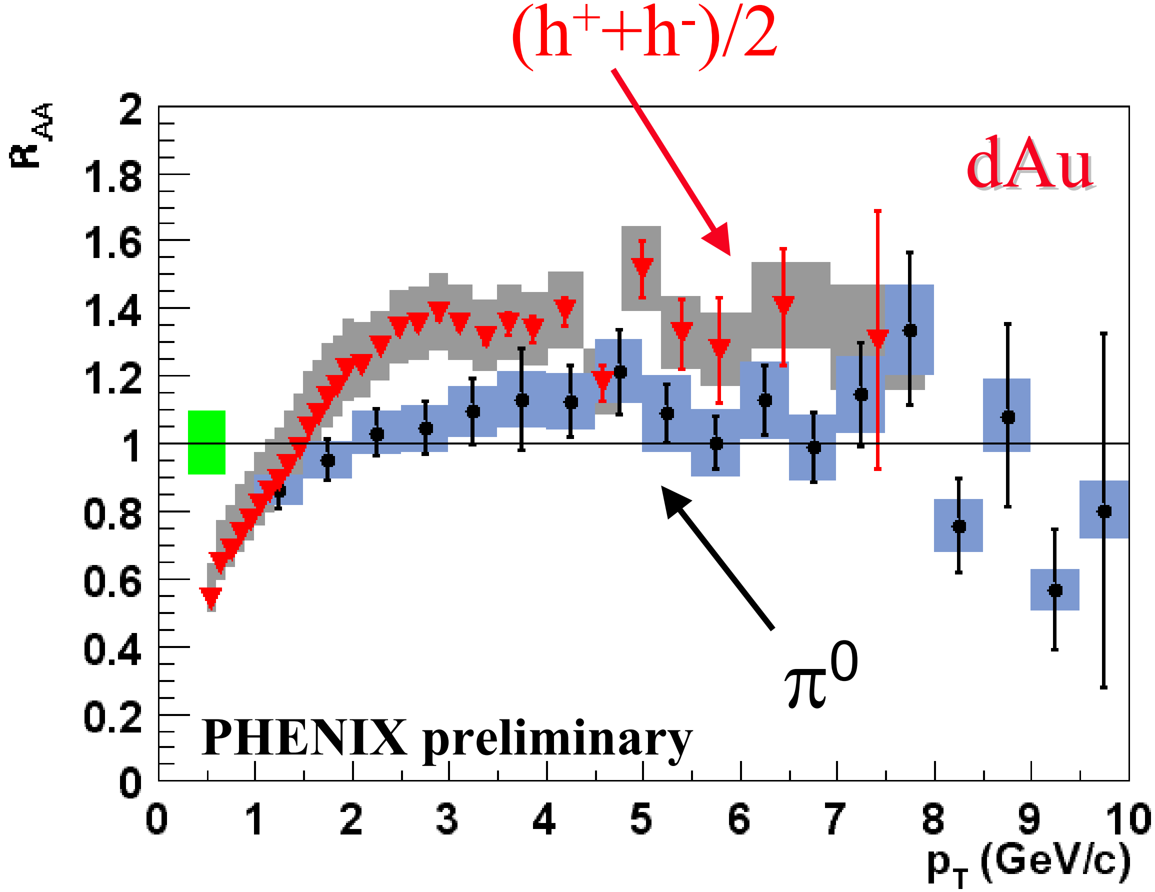



# Do see Cronin effect!

- "Cronin" enhancement more pronounced in the charged hadron measurement
- Possibly larger effect in protons at mid $p_T$

Implication of $R_{dAu}$?

***RHIC at too high x for gluon saturation…***



# $\pi^0$ $R_{AA}$ vs. predictions

Theoretical pre(post)dictions:

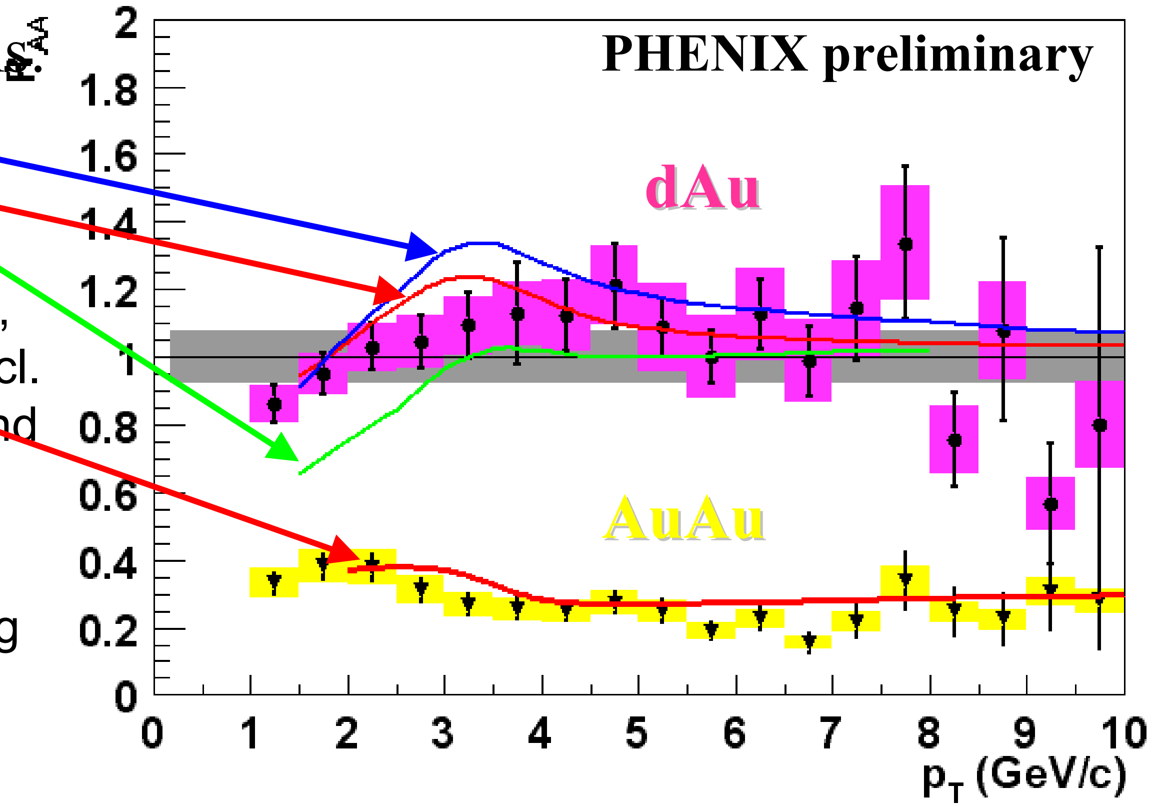
d+Au: I. Vitev, nucl-th/0302002 and private communication.

Au+Au: I. Vitev and M. Gyulassy, hep-ph/0208108, to appear in Nucl. Phys. A; M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, p. 371 (2001).

Initial state: mult. scatt.,shadowing + final state dE/dx (Au+Au)

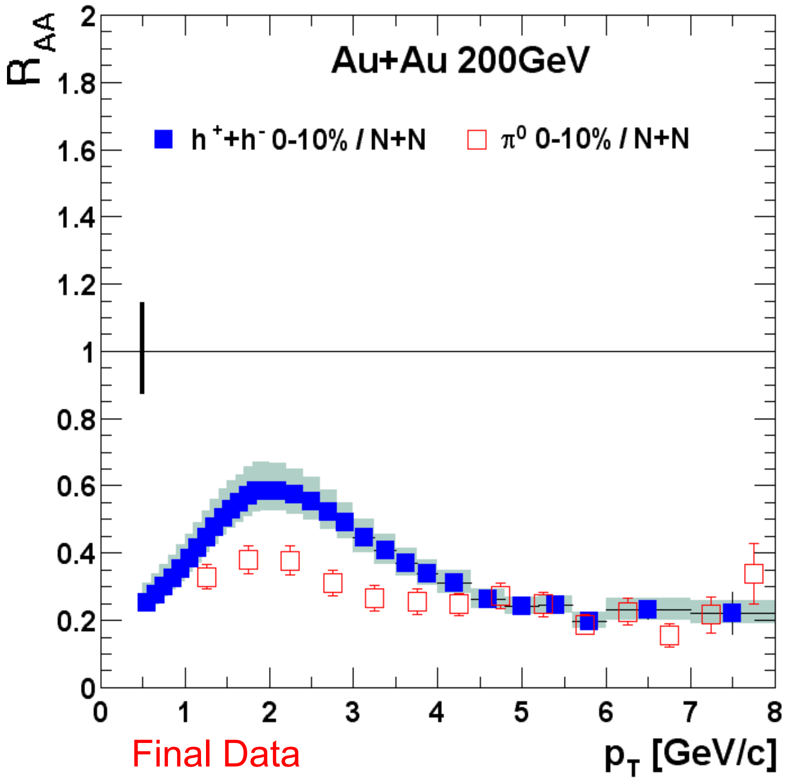
Also: Kopeliovich, et al (PRL88, 232303,2002)

predict $R_{pA}$~1.1 max at $p_T$=2.5 GeV projectile as color dipole



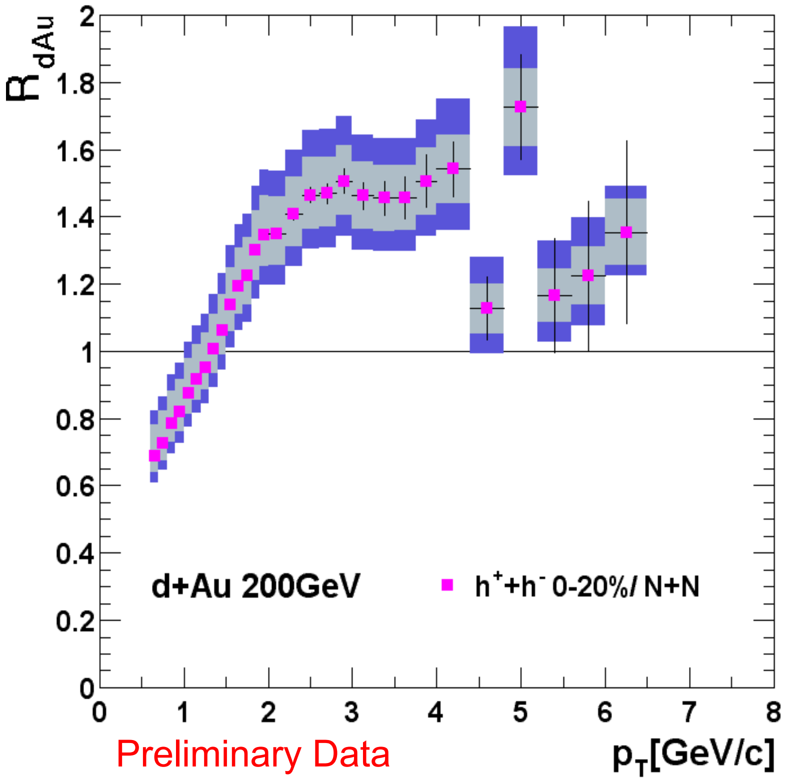
# Centrality Dependence

**Au + Au Experiment**




Final Data

**d + Au Control**




Preliminary Data

**"PHENIX Preliminary"** results, consistent with PHOBOS data in ***submitted paper***

- **Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.**
- **Jet Suppression is clearly a final state effect.**

# summary

- Inclusive $\pi^0$ and chard hadron yields:
  - $R_{AA}$ was meausured in wide range of pT in dAu and AuAu at $\sqrt{s_{NN}} = 200$.
  - Significant suppression, $R_{AA} \approx 0.2$, found in AuAu collisions. "Cronin" like enhancement found in dAu charged hadron spectra and $\pi^0$ $R_{dA}$ is consistent with one.

dAu data left only a little room for the initial state phenomena!

Existence of extremely opaque and "collective" partonic matter seems to be evident!